A CFD study of Hong Kong refuge floor design: Floor height effect

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ABSTRACT

Since 1996, the provision of a refuge floor has been a mandatory feature for all new tall buildings in Hong Kong. These floors are designed to provide for the building occupants a fire safe environment that is also free from smoke. However, the desired cross ventilation on these floors to achieve the removal of smoke, assumed by the Building Codes of Hong Kong, is still being questioned so that a further scientific study of the wind-induced ventilation of a refuge floor is needed. This paper presents an investigation into this issue. The developed computational technique used in this paper was adopted to study the wind-induced natural ventilation on a refuge floor. The aim of the investigation was to establish if a refuge floor with a central core and having cross ventilation produced by only two open opposite external side walls on the refuge floor would provide the required protection in all situations taking into account behaviour of wind due to different floor heights, wall boundary conditions and turbulent intensity profiles. The results revealed that natural ventilation can be increased by increasing the floor height provided the wind angle to the building is less than 90°. The effectiveness of the solution was greatly reduced when the wind was blowing at 90° to the refuge floor opening

1. Refuge Floor Design and Problems

Based on the Building Codes of Hong Kong (MOE: 1996), a refuge floor must be installed in any building with a height of more than 25 storeys. The Hong Kong legislation requires the first refuge floor to be installed on the level immediately above the 25th floor with an additional refuge floor for every 25 storeys thereafter. These refuge floor areas must be fully fire protected and totally separated from the remaining spaces of the building such as a central service core. Fire isolated stairs must terminate at a refuge floor. Plantrooms are prohibited on a refuge unless they are fully separated from the refuge spaces by fire rated separation construction.

The basic aim of a refuge floor is to provide a fire safe area where exhausted evacuees in a fire evacuation can have a brief rest before resuming their escape from the building. It is also a space where disabled persons and toddlers can wait to be rescued by the fire authorities. This concept was intended to protect the occupants who work or live in high rise buildings by enabling them to escape during a fire emergency (Conway 1976). Population density in the tall buildings together with combustible furniture and stationary can present a significant fire hazard. Hong Kong in previous years had experience noticeable loss of life and property damage due to fires in tall buildings when the public spaces were misused. To reduce these incidents, Hong Kong adopted a modification of the Life Safety Code of the National Fire Protection Association (Fire Code of the United States of America NFPA 101: 1991) together with safety concepts proposed by the Council on Tall Building and Urban Habitat (1992). Besides Hong Kong, similar approaches were adopted in Canada (Fire Codes of Canada NBCC 1992), Singapore (Fire Codes of Singapore 2001) and Mainland China (Fire Code of the People's Republic of China GBJ 16-87: 1995).

In addition to the above measures Hong Kong required the provision of refuge floors in high rise buildings. It was soon discovered that it was difficult to prevent the entry of smoke onto a refuge floor in all situations (Satoh and Kuwahara 1991, Sugawa *et al*. 1995, Sugawa *et al*. 1997, Chow and Gao 2000). It should be remembered that smoke is often the major killer in a fire (Hartzell 1987, Tamura 1994, Wu 1997). Occupants escaping in a fire situation are always very sensitive to the smoke, which can spread into their path of travel (Jin and Yamada 1989). Due to this concern, the Building Codes of Hong Kong (1996) required a cross ventilation to be induced on the refuge floor for the removal of the smoke. However, study results of Liu (1975) and Straw *et al*. (2000) raised concerns regarding a simple cross flow because natural wind will flow into the built spaces from both their windward side and leeward side wall openings. Investigations by Ansley (1982) showed that natural ventilation of a built space will be significantly affected by the geometry of its opening. Lam (1992) in a wind tunnel study showed that external wind flow behaviour of a high-rise building was not significantly altered if a permeable floor was added to the building at mid-height level. Ohba *et al*. (2001) in a study showed that wind-induced natural ventilation in a built space will be different when wind is blowing at different angles to the building front face. CFD studies done by Lu *et al*. (2001[a, b, c]) indicated that wind might be logged on a refuge floor if it has numerous small services cores. Refuge floors with multi-service cores occur often in Mainland China but are rarely used in Hong Kong.

The Building Codes of Hong Kong (1996) set the minimum height of the refuge floor as 2.3 m; allowed a large service core to cover up to 50% of the refuge floor area; and required at least two external walls of the refuge floor to be open to induce a cross ventilation for the removal of smoke. Because of concerns raised by previous researchers there is a need to investigate if the minimum requirement of two opposite external side wall openings for a refuge floor with a large central core is adequate to produce the required cross ventilation in all situations. The previous researchers had used numerical methods that required extensive computing power and unfortunately they did not have sufficient scientific physical data to verify the calculated results (Lu *et al*. 2001[a, b, c]). To overcome these problems, wind tunnel experiments were undertaken. The physical wind tunnel data obtained from these experiments formed the scientific base for the evaluation of the simulation results. The wind tunnel tests were performed at the Closed-circuit Boundary Layer wind tunnel of Department of Civil Engineering, University of Hong Kong. Although laser-base anemometry is a popular measuring tool, it is impractical to deploy it to obtain velocity information in the very small gap representing the refuge floor located at the mid-height level of the scaled model due to the complicated reflection and flow disruptions problems. Therefore, 2D hotwire anemometry was adopted to provide the essential velocities information. However, hotwire is well known to give poor measurements of the wake and re-circulation flow. Therefore, only the upwind side velocity information was used for the evaluation. This data was also used to develop effective boundary conditions applied in the fundamental numerical studies (Cheng *et al*. 2005[a, b]) with turbulence of wind being modelled by standard k-ε equations.

Regarding computational flow domain of the simulations, this was based on the physical width and height of the test wind tunnel; i.e. 3m wide and 1.7m high. The length of the domain was designed to provide adequate space for the wind structures to develop over the building model. It was basically at least 1 building height length (h) in front of the building front face and 6 h behind the building rear face. The domain was digitised by tetrahedron elements so that the size of the elements generated around the wall surfaces was determined by the wall function requirement. In general, the maximum size of the elements was restructured to 0.1m. Figure 1 shows a sample digitised vertical plane to outline the basic digitisation applying for a domain. This procedure required less computational resources than that required by similar studies that had been undertaken in the past. Validation of the computed data from this study with the recorded wind tunnel data did show that the simulation results were acceptable. This outcome was achieved by providing realistic turbulent intensity profiles on both inlet and outlet domain boundaries. For brevity, the validation results are not shown in this paper but are provided in the previous published papers (Cheng et al, 2005).

Through these studies, it was found that the desired wind-induced cross ventilation flow could be received at most wind angles provided the square-planned refuge floor had two open sidewalls opened in opposite to each other (Cheng *et al*. 2007[a]). A relative low speed wind re-entered the near wake flow region behind the rear wall of the large central core at most wind angles. The re-entering wind bent towards the building sidewalls and followed the wind exiting the corridor by leaving the refuge floor besides the building sidewalls. However, the wind-induced flow in the corridors became almost a stagnated flow when the wind blew at 90^o to the building front face (wind angle being 90^o). Under this condition, entering smoke in the region might be entrapped and thereby defeat the safety purpose of the refuge floor. In Cheng *et al*. (2007[b]), it was observed that a circular shaped central service core cannot improve the undesirable flow condition when the wind angle is at 90^o. In this situation a small low speed circulating vortex was formed immediately behind the central services rear wall. Unfortunately, this minor flow structure is also unfavourable for purging the smoke. On the other hand, it is believed that the narrow corridors formed by the sidewalls of a building and the sidewalls of a rectangular central service core are important and useful for directing the entering wind from the building windward side opening to pass through the refuge floor and thereby assist in purging the smoke from the floor. Perhaps opening up these external side walls will increase the amount of ventilation flow to pass thought the refuge floor, but an undesirable circulation flow structure would be developed at the refuge space besides this opened side wall such that smoke entered into the space might be prolonged to around the vortex structure. Therefore, the present of the two opposite external building walls has an meaning to this refuge floor design that it can always allow a favourable fire safety condition at most wind angles to purge out entering smoke in the refuge spaces by such introduced channel-like cross flow thought the refuge floor (Cheng et al. 2008, Cheng 2009).

The use of the power equation of turbulent intensity at both inlet and outlet was not considered to be a problem. The native power exponent of the power law equation became undefined when calculating the intensity of flow on the ground (z = 0). Although not required due to the wall-function approach used in the simulation, the investigations undertaken did not find any alternative condition that could be used for maintaining consistency in the simulations. Also investigated in the study was the wind flow due to the computational domain top and side walls (non-slip wall boundaries) which represent the wind tunnel external walls. These boundary conditions forced the velocity of fluid to become zero at these locations and thereby satisfied the condition of a tunnel.

2. Sensitivity Test of Boundary Conditions

Sensitivity tests of the proposed numerical boundary conditions were based on the results obtained in the wind tunnel test (Cheng *et al*. 2005[a]). Due to the physical constraints and the aim of achieving maximum number of measuring points in the wind tunnel test, the building model was scaled at 1:150. H_{rf} of the physical model was constructed to 0.03 h. Due to the physical difficulties of this wind tunnel test, 2-D X-miniature hot-wire anemometry was applied to measure the field wind velocity components. Normal wind velocity component (u) and turbulent intensity (I) above the test point of the wind tunnel test section were analysed and found to follow the power law equations (1) and (2), respectively.

$$u = U_h \left(z/H_h \right)^{0.19} \quad \textit{where } U_h = 10.478 \text{ m/s} \quad \textit{and} \quad H_h = 0.85 \text{ m above floor} \qquad \ldots.. (1)$$

$$I = I_h \left(z/H_h \right)^{-0.47} \quad \textit{where } I_h = 0.088 \quad \text{and} \quad H_h = 0.85 \text{ m above floor} \qquad \ldots.. (2)$$

Note: a.) u is the velocity component flowing along the normal axis of the wind tunnel; i.e. x-axis
b.) I is the turbulent intensity of wind

In this situation the velocity component, v (velocity component at the normal axis y) and velocity component, w (velocity component at the vertical axis z) were set equal to 0 m/s to enable manageable calculations to be replicated, at an acceptable level, the conditions measured in the wind tunnel experiments. In addition, the difference between the inlet and outlet was also set as 0 because the wind structures had been fully developed in the floor domain. Computational domain walls were considered to be non-slip boundary walls. A full description of the wind tunnel test and validation of the numerical method used can be obtained in the paper by Cheng et al. (2005[a]).

The sensitivity test of study was undertaken by testing an alternative I-profile as non-slip and free-slip domain boundary wall conditions. This profile was formed by a constant I which was described as a percentage;

i.e. 1% was tested first. Since hot-wire anemometry provides poor measurement of the re-circulation flow, only recognised windward side data was used in the analysis. By observation of Fig. 2, computation of the wind field velocity components was found to be not sensitive to the selected wall boundary conditions. Also those simulation results provided good agreements with the wind tunnel data. The computed results of I = 1%, 5% and 10% were compared with the recognised data and the investigation method where the domain boundary walls were in a non-slip boundary condition. As shown in Fig. 3, the computational method was not sensitive to the proposed I-profile boundary condition. To maintain the robustness of the simulation results, boundary conditions developed by the physical wind tunnel data (original method) were applied in the remaining part of this study.

3. Wind-induced Natural Ventilation of the Refuge Floors of Different H_{rf}

To establish the amount of wind-induced natural ventilation passing through the refuge floors a non-dimensional coefficient was employed:

$$C_m = \frac{\int \left(\vec{u}\right) d\vec{A}}{A_w U_H}$$

where:

$\int \left(\vec{u}\right) d\vec{A}$ is the integration of the normally acting intake velocity

A_w is the total cross sectional area of the openings of the refuge floor of a nominal height with 2 opposite sides opened to the outside

U_H is the reference velocity acting on the domain inlet at building height level.

Five cases with different refuge floor heights were studied; i.e. H_{rf} = 0.01 h (1.2 m in real scale), 0.02 h (2.4 m in real scale), 0.03 h (3.7 m in real scale), 0.05 h (6.4 m in real scale), and 0.1 h (13.4 m in real scale). H_{rf} = 0.01 h (1.2 m in real scale) was included in the study for academic reasons to establish the effect of a low refuge floor height even though it is not permitted by the Building Codes of Hong Kong which has set 2.3 m as the minimum height of a refuge floor. Table 1 shows that the amount of natural ventilation that can be received by a refuge floor is dependent on both wind incident angle and the refuge floor height (H_{rf}). As one would expect with increasing refuge floor height the volume of wind received is increased. Almost equal amount of natural ventilation was received by a refuge floor facing the prevailing wind at a normal incident angle or at 45^o. However, the amount of natural ventilation was substantially reduced when the wind was blowing at 90^o (perpendicular) to the building front face. With the wind blowing at 90^o to the front face of a H_{rf} = 0.01 h refuge floor, only the minimum amount of natural ventilation could be delivered; i.e. C_m = 0.0006. For refuge floor heights of H_{rf} = 0.02 h and H_{rf} = 0.03 h the natural ventilation quantity was not significant for all three wind incident angles. When the refuge floor height (H_{rf}) was taller than 0.05 h, the natural ventilation became significant especially for incident angles 0^o and 45^o as shown in Table 1.

Table 1. C_m of different H_{rf} refuge floors at selected wind incident angles

H_{rf}	Wind Incident Angles		
	0^o	45^o	90^o
0.01 h	0.00258	0.00198	0.00056
0.02 h	0.00692	0.00642	0.00133
0.03 h	0.01134	0.00840	0.00287
0.05 h	0.02168	0.02042	0.00405
0.1 h	0.04822	0.04165	0.00878

Besides C_m, normalised wind field velocity vectors and pressure coefficient (C_p) distribution over the symmetry horizontal plans of these floors are presented (see Fig. 4). Velocity vectors depicted in the figures are constructed by computed velocity coefficients u/U_o nad v/U_o, where U_o is the reference velocity component u of domain inlet flow plane at building height level. Fig. 4.a showed that a longer trailing flow is formed following the channel-like flow passing through the internal corridors of a taller refuge floor when wind is blowing at normal incident angle to the building front face. However, the channel-like flow forming at the corridors of a H_{rf} = 0.01 h refuge floor is very weak. C_p contour plan H_{rf} = 0.01 h shown in Fig.4.b indicated that a favourable pressure gradient on the side wall corners was not well developed. However, when H_{rf} = 0.02 h a favourable pressure gradient on the leeward side around the building side wall corners was established and becomes well developed at where H_{rf} = 0.1 h. Meanwhile, high wind pressure acting on the front of the central services core increased with an increase in H_{rf} so that diffusion of wind-induced flow exiting from a refuge floor on its leeward side will be reinforced if H_{rf} was taller. This was confirmed by the wind patterns illustrated by Figure 4.a.

When the wind is blowing at 45^o to the building front face, similar wind vortex structures as shown in Fig. 4.a and 4.b were repeated (see Fig. 4.c and 4.d). By observation of these figures, the leading edge of a refuge floor encouraged the prevailing natural wind to splash through the floor and a stronger channel-like flow was induced in the corridor located adjacent to the leading corner. On the opposite side, exiting trailing flow curved inward to the middle behind the refuge floor rear side wall opening. Comparing Fig. 4.c with Fig. 4.d, it can be seen that an increased pressure gradient developed in diffusing the exiting wind from the refuge floor where the clear floor height was taller. However, in the case of the weak side corridor of the refuge floor with H_{rf} = 0.01 h, a major flow structure was not fully developed. Therefore wind flowing over more or less half of its refuge area is almost stagnated.

The channel-like flow induced at the refuge floors internal corridors was diminished when wind was blowing at 90^o to the building front face (see Fig. 4.e). Flow induced at the middle of these corridors was often found to be almost stagnated for all H_{rf} test cases. Comparing Fig. 4.a, 4.c, and 4.e, separation flow regions adjacent to the building side walls were not significantly enlarged by increasing the blocking side wall area to the prevailing wind of the refuge area as the wind angle was increasing from 0^o to 90^o in all cases. On the other hand with a wind angle of 90°, an adverse pressure gradient was developed adjacent to the rear side wall corner of the refuge floor (see Fig. 4.f) so that it encouraged the wind re-attachment to the refuge floor and this increased slightly in case of a taller H_{rf} (see Fig. 4e).

4. Implications on the refuge floor designs

From the above analysis using only two side walls of the refuge floor open, desirable cross ventilation can be obtained by the selected H_{rf} refuge floors at most wind angles. Generally, wind-induced flow will purge accumulating smoke in the refuge area except when wind was blowing at 90^o to the building front face. Corridors in taller H_{rf} will not achieve a substantial increase in the induced wind flow when the wind is at 90° to the building. In this latter situation, the increase in dragging of re-attachment wind on the leeward side wall corners could cause spilling smoke around the region to be dragged into the refuge space again. On the other hand, excessive increase in H_{rf} will lead to significant increase in construction cost plus structural and aesthetic problems for the building designers. These problems are often the barriers of implementing the design in many countries. In some situations, it could be a significant problem where the total building height is controlled by a town plan as in Australia, which currently does not require the use of refuge floors.

5. Conclusion and Recommendations

Wind-induced natural ventilation to the refuge floors of different H_{rf} was investigated. Computed results undertaken were not significantly altered by non-slip or free-slip domain wall boundary condition. Furthermore, they were not obtained by applying different wind turbulent intensity boundary conditions of the power law equation or a constant. In order to protect the consistency and robustness of the results, the original CFD method (Cheng 2007[c]) was applied in the present study. The wind velocity patterns presented in this study indicated that increasing H_{rf} can create favourable condition to achieve the desired wind-induced natural cross ventilation required by the Building Codes of Hong Kong (1996) in most cases. However, increasing the height of the refuge floor does not solve the potential smoke problem when wind blowing at 90^o toward the building front face. Higher dragging force of re-attachment wind around the leeward side wall corners is of concern. There are some practical design, construction and cost issues associated with tall refuge floors such as the 0.05 h (H_{rf} = 6.4m in real scale) or 0.1 h and 0.1 h (H_{rf} = 13.4m in real scale).

From a practical point of view, the study results showed that refuge floors with a minimum of two opposite external openings built at a range of 0.02 h to 0.03 h tall are acceptable in most situations but could encounter problems when the wind is blowing at 90° to the refuge floor openings. To overcome this 90° wind situation and to improve the cross ventilation, a mechanical fan system would be suggested to be installed at their internal corridors so as to ensure a reasonable driving force for the induced flow to splash through the refuge area. Although an active fan system can be a good solution for the present potential problem but the working conditions of this system will be dependent on a number of issues such as the building maintenance practice and also the provision of a secure power source during a fire situation. Another study will be suggested for the design of this system. Nonetheless, passive building features to achieve the desired wind-induced flow effect for the refuge floor is still needed. Based on the studies undertaken there are sufficient signs to indicate that the passive refuge floor effectiveness can be achieved by having different internal wall layouts. It is suggested that this concept should be explored.

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FIGURE CAPTIONS

Fig.1. Sample digitised symmetry vertical flow plane with a 0.02*H* refuge floor installed at the building mid-height level

Fig.2. Wall boundaries sensitivity test results of original and 1% turbulent intensity CFD methods: (a) Vertical symmetry plane (y = 0), (b) Horizontal symmetry plan (z/H_h = 0.6)

Fig.3. CFD turbulent intensity profiles sensitivity test results: (a) Vertical symmetry plane (y = 0), (b) Horizontal symmetry plan (z/H_h = 0.6)

Fig. 4. Computed wind field velocity vectors and C_p patterns of the horizontal symmetry plane of different H_{rf} refuge floors: (a) Computed wind field velocity vectors plan for wind incident angle = 0^o, (b) Computed wind field C_p contour plan for wind incident angle = 0^o, (c) Computed wind field velocity vectors plan for wind incident angle = 45^o, (d) Computed wind field C_p contour plan for wind incident angle = 45^o, (e) Computed wind field velocity vectors plan for wind incident angle = 90^o, (f) Computed wind field C_p contour plan for wind incident angle = 90^o

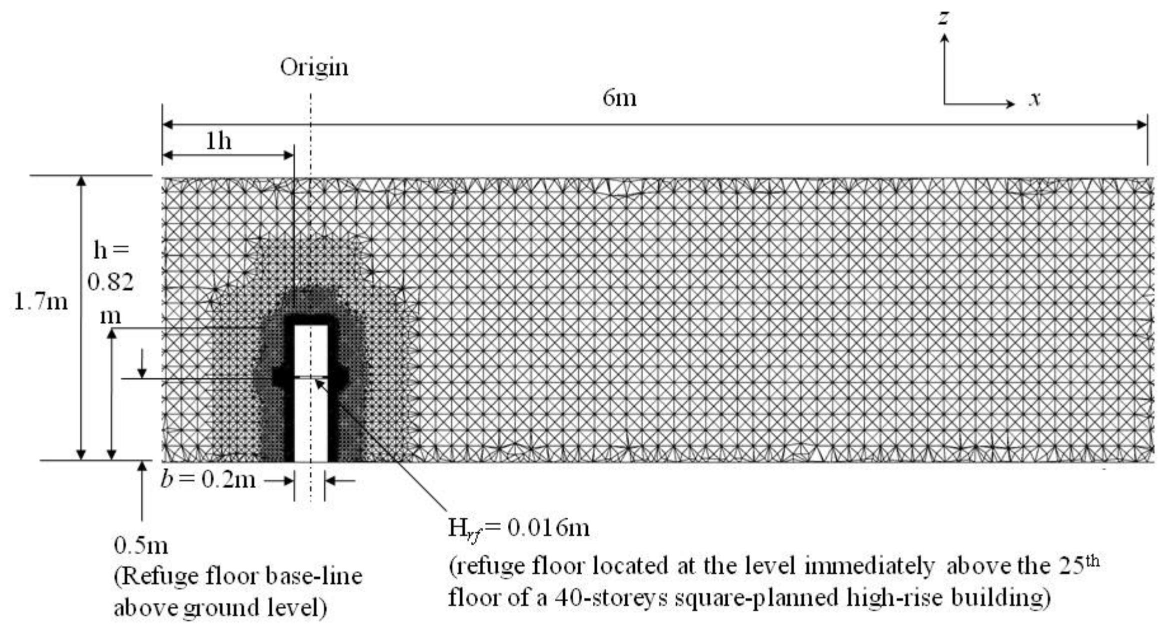
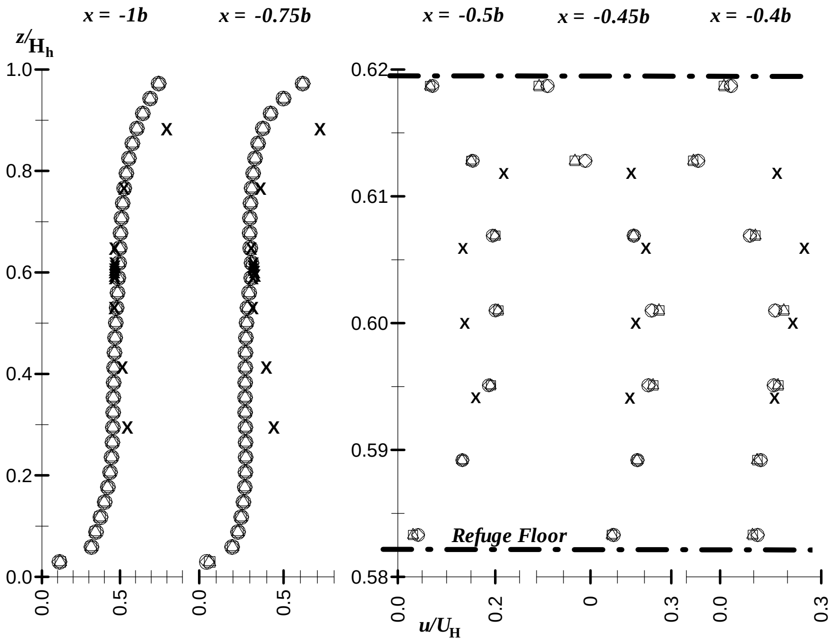
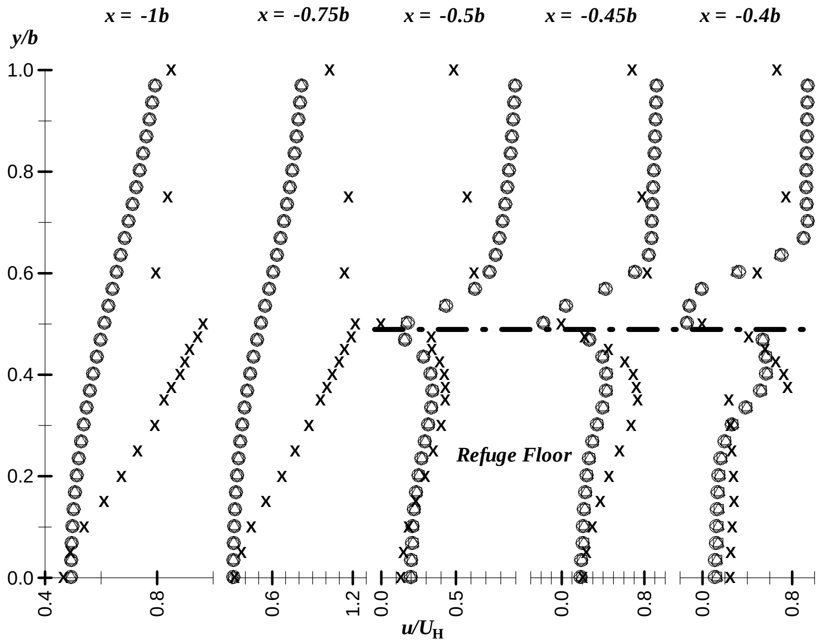


Fig. 1. Sample digitised symmetry vertical flow plane with a 0.02 h refuge floor installed at the building mid-height level



(a) Vertical symmetry plane (y = 0)

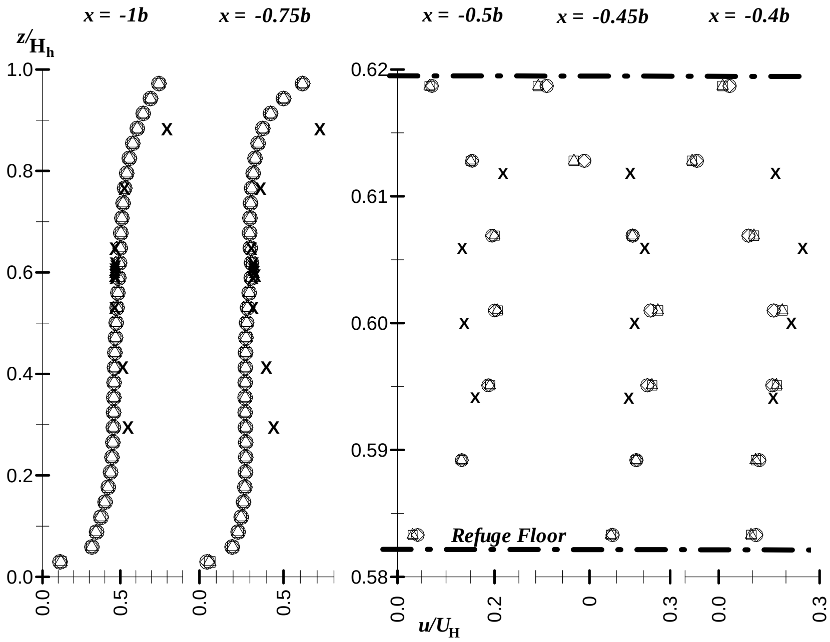


(b) Horizontal symmetry plan (z/H_h = 0.6)

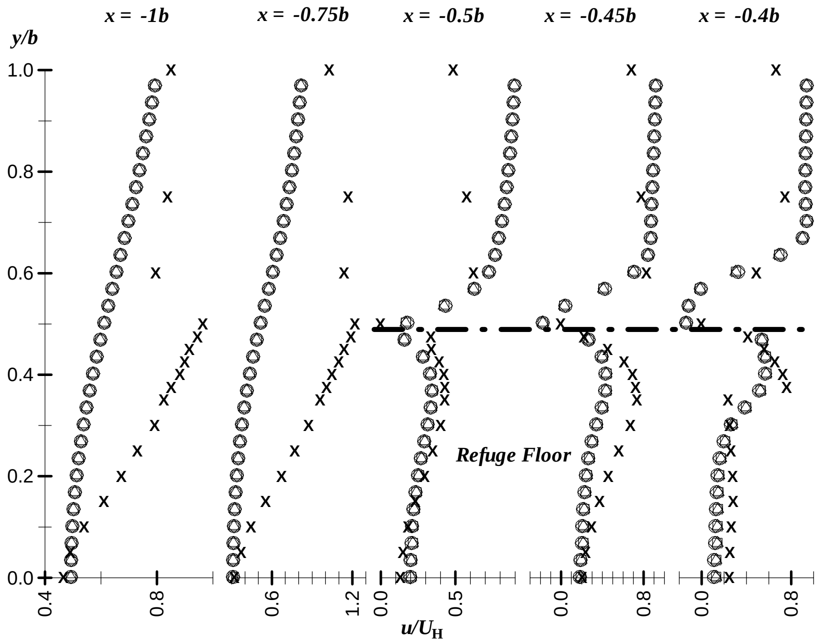
Symbols (u/U_H)

X	Wind tunnel data
□	Computed velocity coefficients obtained by using original method
△	Computed velocity coefficients of original method when free-slip domain wall boundary condition applied
◇	Computed velocity coefficients of I = 1% and non-slip domain wall boundary condition applied
○	Computed velocity coefficients of I = 1% and free-slip domain wall boundary condition applied.
U_H	reference velocity component (u) taken at H_h level of the CFD domain inlet plane or reference point of the wind tunnel test section

Fig.2. Wall boundaries sensitivity test results of original and 1% turbulent intensity CFD methods



(a) Vertical symmetry plane (y = 0)

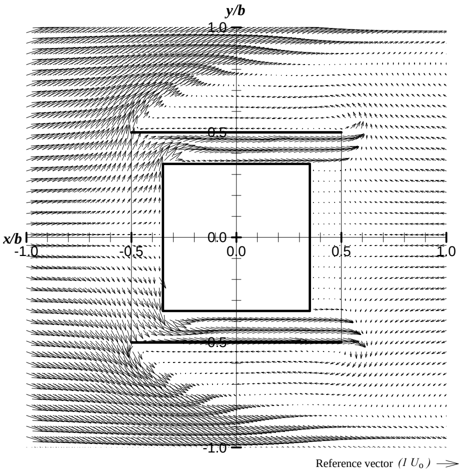


(b) Horizontal symmetry plan (z/H_h = 0.6)

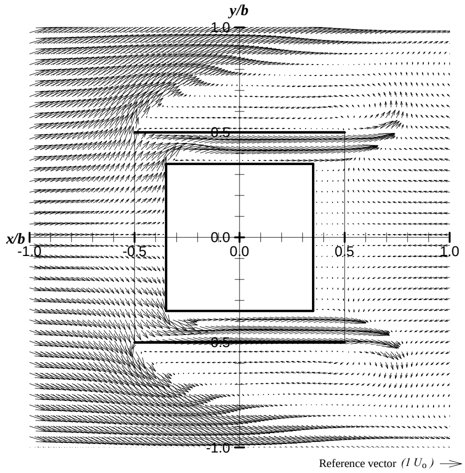
Symbols (u/U_H)

X Wind tunnel data
□ Computed velocity coefficients obtained by using original method
△ Computed velocity coefficients obtained by I = 1% profile applied
◇ Computed velocity coefficients obtained by I = 5% profile applied
○ Computed velocity coefficients obtained by I = 10% profile applied
U_H reference velocity component (u) taken at H_h level of the CFD domain inlet plane or reference point of the wind tunnel test section

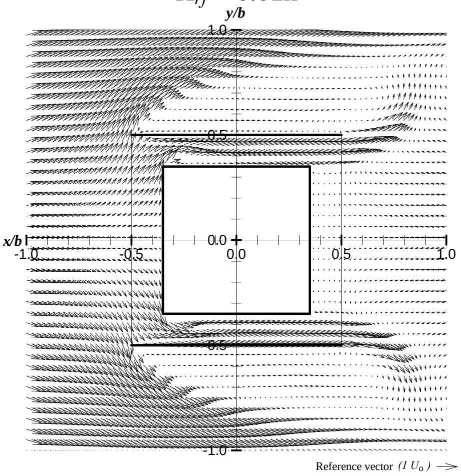
Fig.3. CFD turbulent intensity profiles sensitivity test results



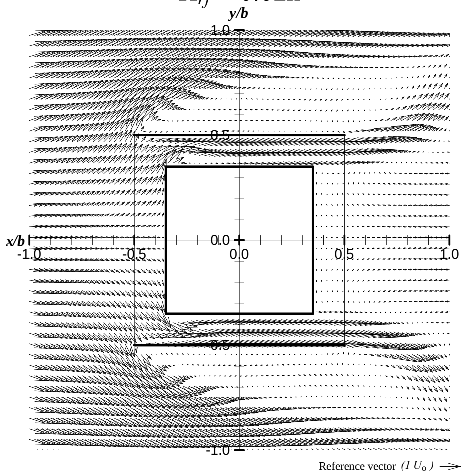
$H_{rf} = 0.01h$



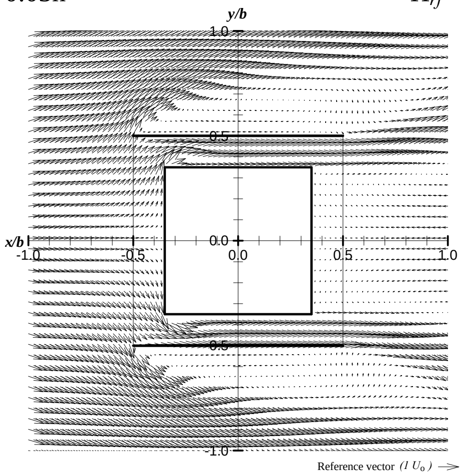
$H_{rf} = 0.02h$



$H_{rf} = 0.03h$

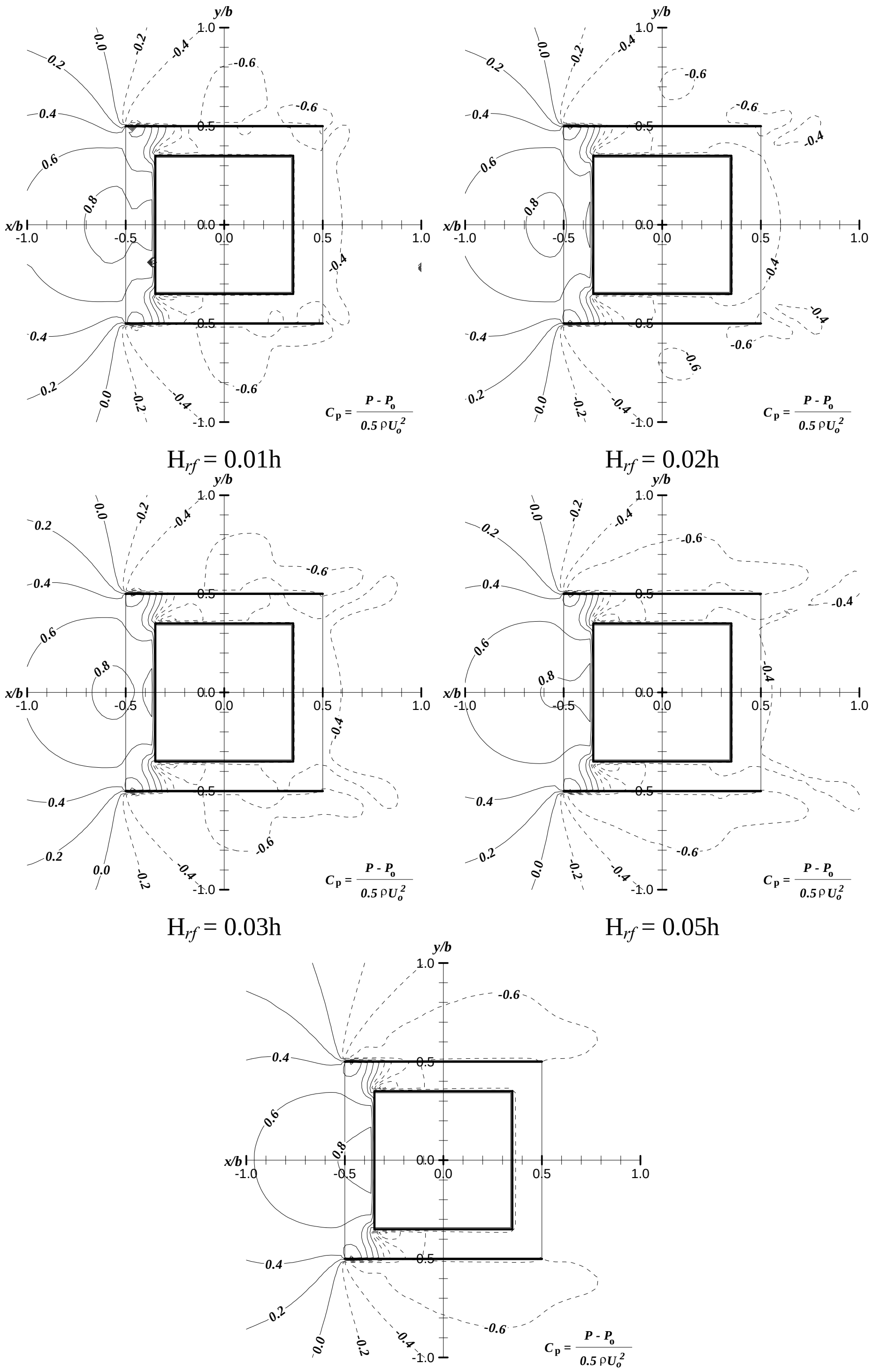


$H_{rf} = 0.05h$



$H_{rf} = 0.1h$

(a) Computed wind field velocity vectors plan for wind incident angle = 0^o

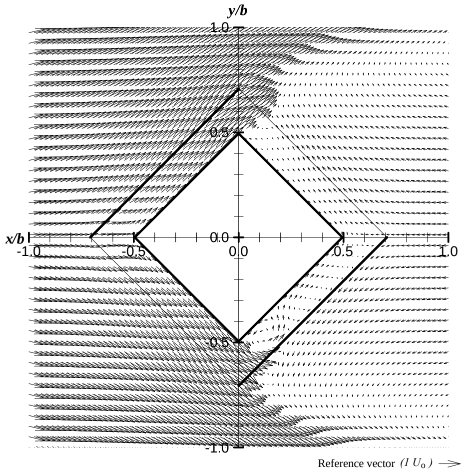


H_{rf} = 0.01h H_{rf} = 0.02h

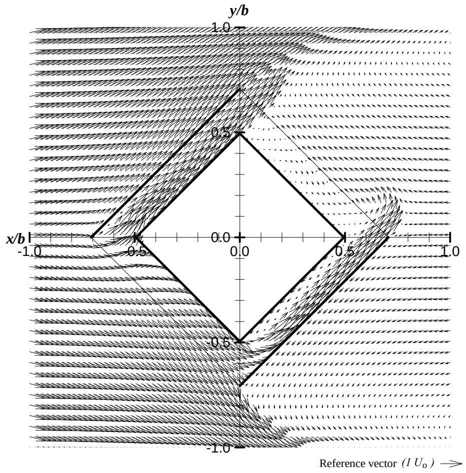
H_{rf} = 0.03h H_{rf} = 0.05h

H_{rf} = 0.1h

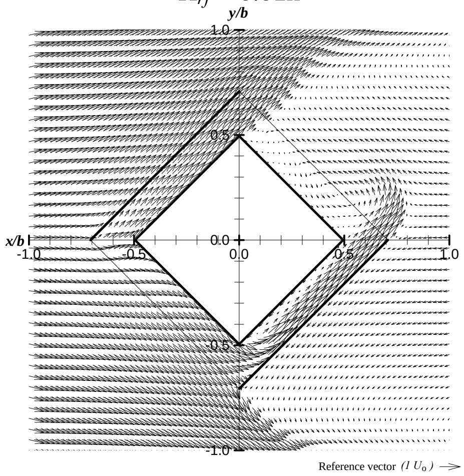
(b) Computed wind field C_p contour plan for wind incident angle = 0^o



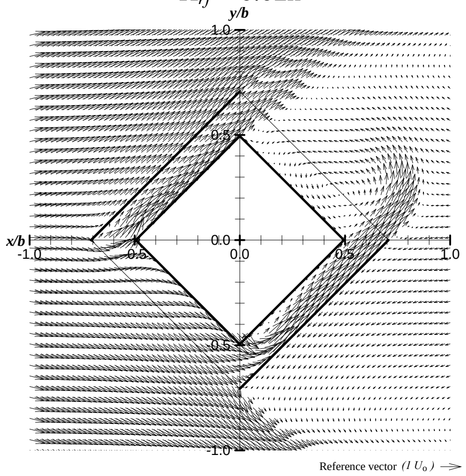
H$_{rf}$ = 0.01h



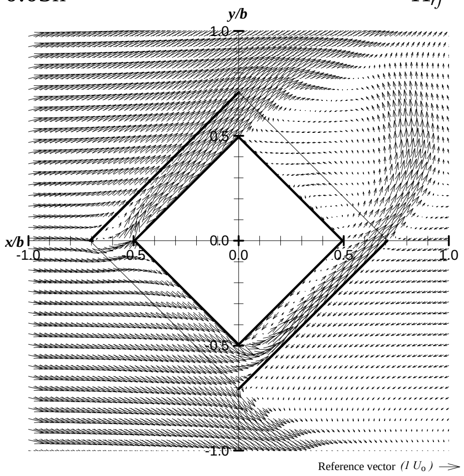
H$_{rf}$ = 0.02h



H$_{rf}$ = 0.03h

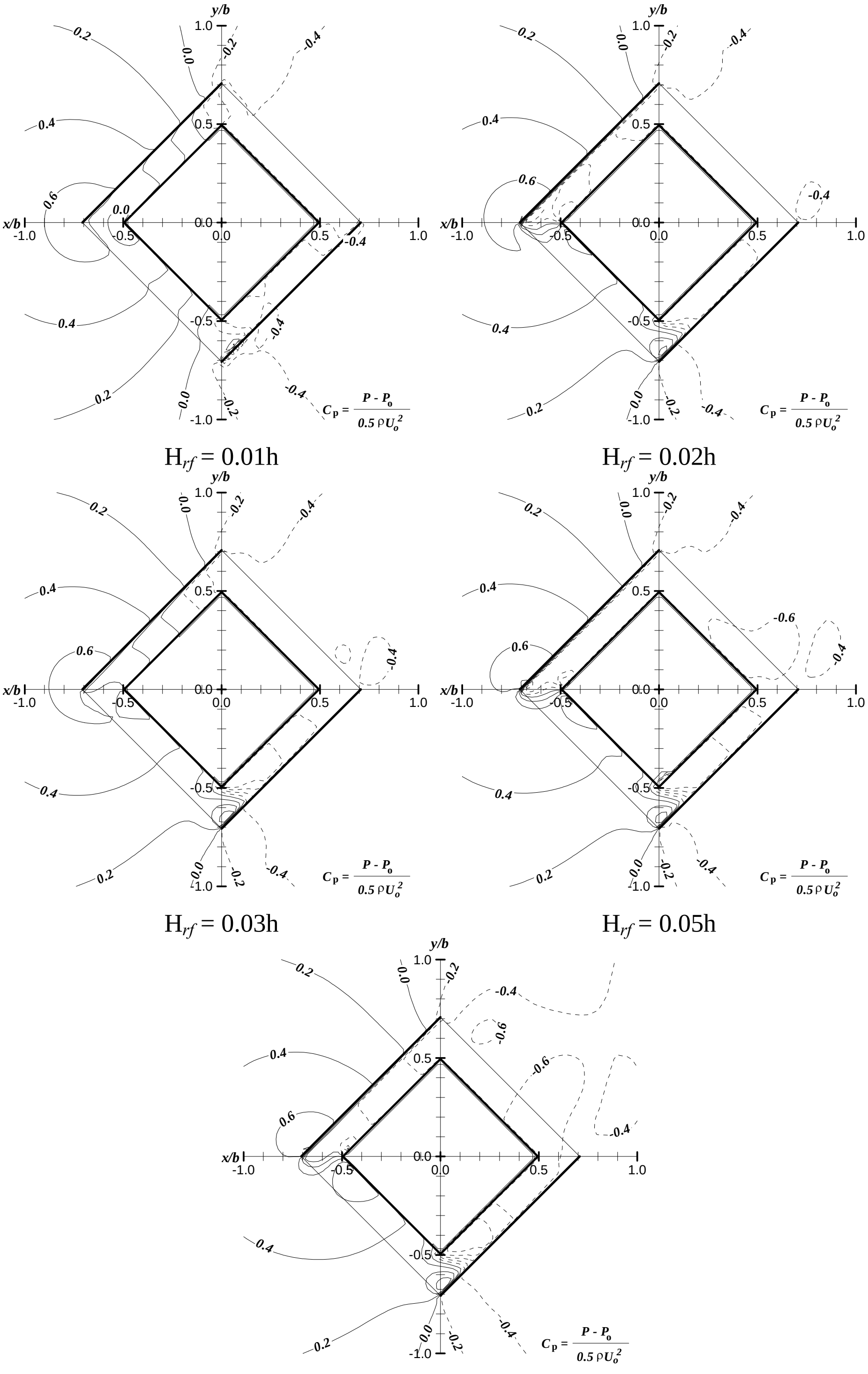


H$_{rf}$ = 0.05h

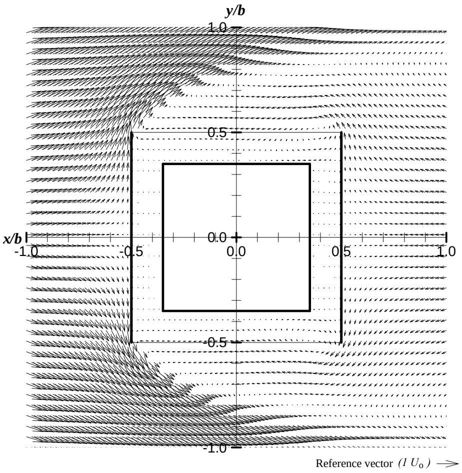


H$_{rf}$ = 0.1h

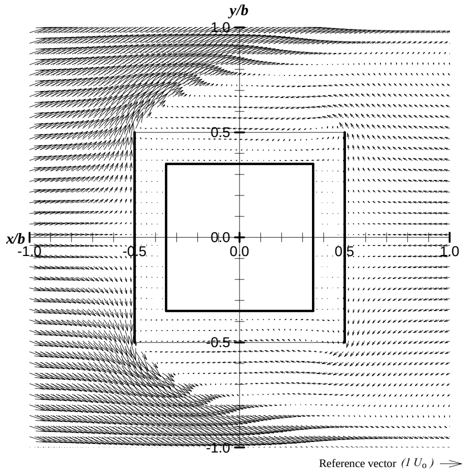
(c) Computed wind field velocity vectors plan for wind incident angle = 45^o



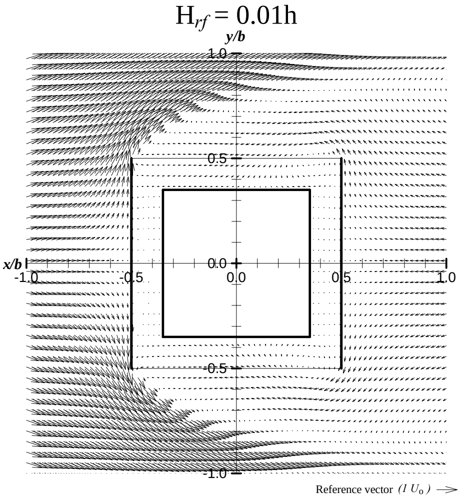
(d) Computed wind field C_p contour plan for wind incident angle = 45^o



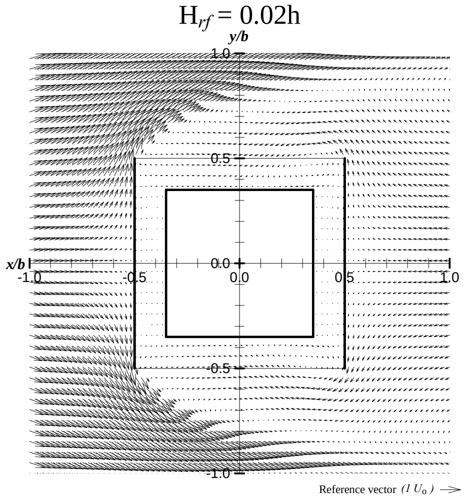
H_{rf} = 0.01h



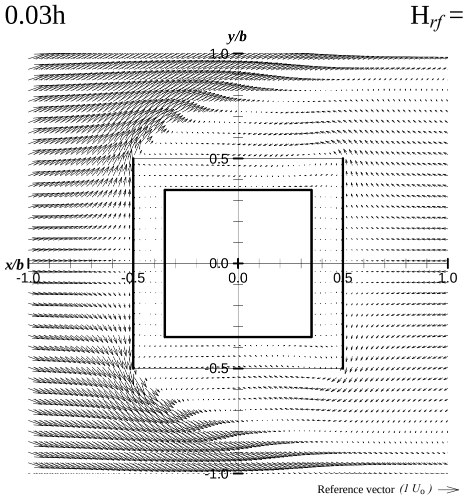
H_{rf} = 0.02h



H_{rf} = 0.03h

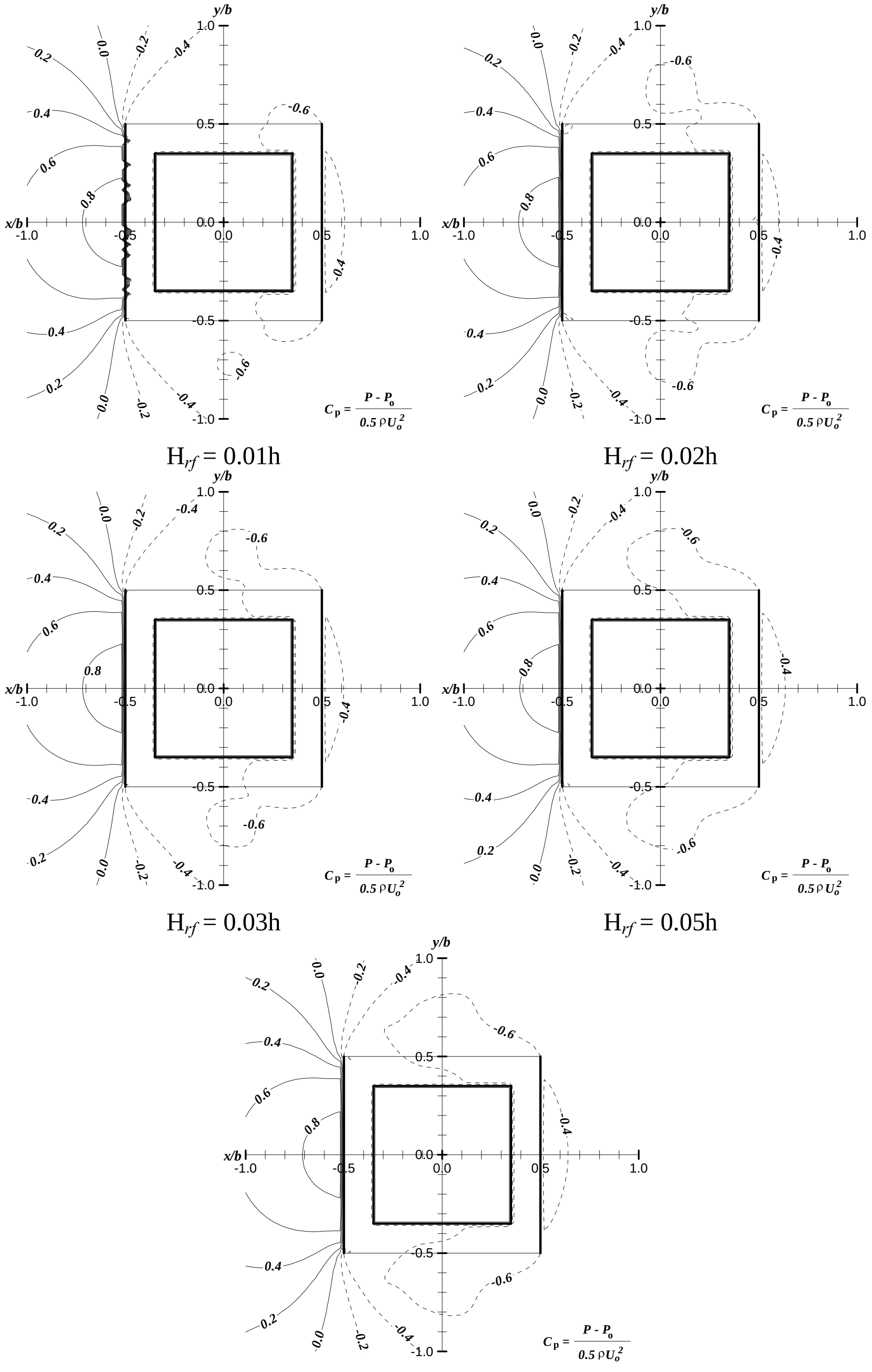


H_{rf} = 0.05h



H_{rf} = 0.1h

(e) Computed wind field velocity vectors plan for wind incident angle = 90^o



$H_{rf} = 0.01h$ $H_{rf} = 0.02h$

$H_{rf} = 0.03h$ $H_{rf} = 0.05h$

$H_{rf} = 0.1h$

(f) Computed wind field C_p contour plan for wind incident angle = 90^o

Fig. 4. Computed wind field velocity vectors and C_p patterns of the horizontal symmetry plane of different H_{rf} refuge floors